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Original scientific paper

Analysis of Kerf Width and its Variation in CO_2 Laser Cutting of Straight and Curved Cut Profiles

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Abstract: Geometrical characteristics of obtained kerf are important quality indicators in laser cutting. Considering that they are differently affected by a number of factors, this study is focused on the analysis of kerf width and its variation in CO_2 laser cutting of straight and curved cut profiles. For the purpose of analysis and modeling of possible curvatures in considered outputs, a three-level full factorial design with replication was performed by considering severance energy and nitrogen pressure, which play a key role in the mechanisms of melting and ejection of molten material from the kerf. Based on experimental results multiple analysis were conducted including the analysis of the effects of severance energy and nitrogen pressure on kerf width and its variation on both straight and curved cut profiles. Further, by developing four prediction models and using overlay contour plots, simultaneous analyses of the kerf width and its variation were performed for both profiles and favourable cutting conditions were identified. The obtained results and observations made indicated favourable conditions for kerf width minimization and its variation, which, however, do not coincide for both cutting profiles.

Keywords: 316L stainless steel; CO_2 laser cutting; curved cut profile; kerf width; kerf width variation; straight cut profile

1 INTRODUCTION

Kerf geometry is a very important quality performance for all contour cutting technologies. In laser cutting research and practice it is usually assessed in terms of kerf width (upper and lower), kerf deviation (unevenness) and kerf taper (cut perpendicularity). Among these, kerf width has been predominantly considered in empirical, theoretical, and numerical laser cutting investigations. It is a very important process indicator because it represents a basis for efficiency, productivity, and quality evaluation with regard to the selected conditions [1-3]. As noted by Alsaadawy et al. [4], it plays a key role in determining the overall performance of the laser cutting process.

Kerf width represents the width of the cut opening (slot, groove) that is formed during the cutting process, which tends to be somewhat narrower at the laser beam exit side [5]. Kerf width values that can be achieved in laser cutting range from 0.1 to 0.5 mm [6]. The obtained kerf width depends on a number of factors, including material properties (metallurgical, thermal characteristics, reflectivity etc.), sheet thickness, laser beam properties, focal length, focus position, orifice diameter, stand-off distance, main control process parameters, etc. Among these, laser beam properties particularly play a significant role, not only regarding kerf geometry, but also process efficiency, productivity, and overall quality [7]. In addition, kerf width variations may be affected by the workpiece's surface conditions and contamination of focusing optics [8]. When comparing the two most common laser cutting methods in the industry, i.e., reactive and fusion cutting, cutting with nitrogen produces more uniform and narrower kerf [9]. Kerf width is often considered when highlighting the advantages of laser cutting technology over the other contour cutting technologies. Attainable kerf widths in abrasive water jet cutting and plasma arc cutting relative to the laser cut kerf width are in ratios of 3:1 and 4:1, respectively [8].

The process of laser cutting under the conditions which produce increased kerf width cannot be considered even near optimal because of the unnecessary excessive heat input into the sheet material and probable deterioration of the overall cut quality. Such conditions signal that it is probably possible to achieve higher productivity levels by an increase in the cutting speed which would decrease laser beam material interaction time, i.e. heat input, as well as kerf width. Achieving as small kerf width as possible is a more favourable case, because of material savings and the ability to maintain dimensional accuracy when cutting small features and sharp corners [10], but not necessarily the best. This is particularly related to laser fusion cutting, where too narrow kerf width prevents efficient melt ejection which creates the conditions for dross formation. Therefore, target kerf width needs to be adequately chosen, so as to improve the laser cutting process in terms of repeatability and reliability [8]. In addition, the selection of a particular laser cutting regime for the attainment of prespecified kerf width would simplify part programming and improve dimensional accuracy [11].

Because of its multiple significance, a number of studies have analysed how different factors affect kerf width in laser cutting of mild steel [12-15], stainless steels [14, 16-18], aluminum and its alloys [14, 19], composites [20, 21], titanium alloys [22], superalloys [23], copper [24], polymers [25, 26], wood [27, 28], granite [29], etc. In an attempt to optimize the laser cutting process, real time kerf monitoring systems are also being developed and implemented [30-32].

Kerf taper refers to the perpendicularity deviation of cut surfaces, i.e., the distance between two parallel straight lines between which the cut surface profile is inscribed and positioned within the set angle [33]. It represents an inherent undesirable geometrical feature of laser cutting, mainly due to the converging-diverging laser beam shape [34], which affects the obtained feature dimensional accuracy [35]. Analysis and minimization of kerf taper is especially important for larger sheet thicknesses and can be achieved by properly focusing and selecting cutting parameters. It can be determined by direct measurements or indirectly by calculation, knowing the upper and lower kerf widths, and the thickness of the sheet.

The actual laser cutting process is characterized by multiple stochastic phenomena, including temporal variations in laser output power, optical integrity perturbations, fluctuations in absorbed power, assist gas pressure and flow fluctuations, plasma formation, variable melt film morphology and flow properties, etc. [12, 16, 36]. In addition, the noise effects, related to sheet thickness variation and material inhomogeneity, cause process variability, which is evident in different cut quality characteristics, including kerf deviation (kerf unevenness). Kerf deviation is often expressed as a difference between maximal and minimal kerf width along a section of cut [37, 38]. Due to the fact that the uniformity of the cut is important for end product quality [13], some authors have considered analysis and optimization of kerf deviation. Chaki et al. [39] applied the Taguchi method along with multiple *S*/*N* ratios for multi-response optimization of kerf width and kerf deviation in Nd:YAG laser cutting of aluminum alloy. Grey fuzzy logic methodology was applied by Das et al. [40] to determine optimized conditions in Nd:YAG laser cutting of nickel-based superalloy with respect to kerf taper, kerf deviation and kerf width. Gautam and Pandey [41] applied multiple regression models and a teaching learning metaheuristic algorithm for kerf deviation minimization in Nd:YAG laser cutting of Kevlar-29 composite laminates. Rajamani and Tamilarasan [42] used fuzzy and regression models for predicting kerf deviation and material removal rate in Nd:YAG laser cutting of Ti-6Al-4V superalloy with respect to four processing parameters. Khoshaim et al. [43] analysed the effect of sheet thickness, laser power, assist gas pressure and cutting speed on kerf deviation in CO_2 laser cutting of polymethylmethacrylate. The analysis of kerf deviation in Nd:YAG laser cutting of a basalt-kevlar 29-glass fiber based hybrid composite laminate was performed by Mishra et al. [44]. Artificial intelligence methods were applied by Najjar et al. [45] to model, analyse and optimize three kerf quality characteristics in Nd:YAG laser cutting of basalt fibers reinforced polymer composites. Singh et al. [22] applied Taguchi's optimization methodology for kerf quality characteristics optimization in Nd:YAG laser cutting of titanium alloy.

Unlike analysis of kerf geometry on straight cut profiles, a very limited number of experimental, modeling and optimization studies have been reported regarding curved cut profiles. The following few studies have addressed this issue in Nd:YAG laser cutting of nickel based superalloy and titanium alloy. For optimization of kerf deviation, kerf width and kerf taper, Sharma et al. [37] applied Taguchi's optimization methodology, while Rao and Yadava [46] applied a hybrid approach, i.e., Taguchi methodology coupled with grey relational analysis. Fuzzy logic (FL) and grey relational analysis were used by Joshi and Sharma [47] for simultaneous optimization of kerf deviation and kerf taper. Pandey and Dubey [38] developed a fuzzy expert system, based on an integrated ANN-FL approach, for the prediction of kerf deviation and kerf width. Regarding CO_2 laser cutting, Parthiban et al. [19] applied FL for modeling the relationships between process inputs and process outputs (kerf width and kerf deviation) in cutting curved cut profiles in aluminum alloy. Parthiban et al. [17] also made a comparison of kerf widths for straight and curved profiles in CO_2 laser cutting of AISI 316L stainless steel.

From the viewpoint of practical application of the laser cutting technology, the multifold importance of kerf geometrical characteristics is clear. Given that kerf geometry depends on the cut profile [37], the aim of the present study is to analyse kerf width and its variation in CO_2 laser cutting of stainless steel 316L considering straight and curved cut profiles. Unlike the majority of previous research studies, this study considers the kerf variation, expressed through the standard deviation, whose values were obtained by replicating the full factorial experimental design. The research is additionally motivated by the limited number of CO_2 laser cutting studies dealing with this topic, particularly regarding the cutting of curved profiles. Since kerf quality characteristics can be improved by adequate determination of cutting conditions [40], empirical studies in laser cutting with appropriate application of design of experiments, modeling and optimization methods create conditions for a more comprehensive process analysis aiming at exploiting the full capabilities of the laser cutting technology. Moreover, it is of utmost importance for cost minimization and optimal utilization of available resources [48].

2 EXPERIMENTAL SETUP AND DETAILS

A 2 mm thick AISI 316L stainless steel sheet (Marcegaglia, Italy) was used for experimentation. A CO_2 laser cutting machine Prima Power Domino Evoluzione (Fig. 1), with the maximal output power of 4000 W and 0.03 mm positioning accuracy and repeatability, was used for cutting. The lens focal length, focus position, orifice diameter and stand-off distance were 190.5 mm, 2 mm, 1.5 mm, and 0.7 mm, respectively. Focusing the laser beam to the bottom surface of the sheet is advantageous in laser fusion cutting of stainless steels and aluminium alloys to improve cut quality and reduce dross formation [8]. Nitrogen at a purity level of 99.999% was used as assisting gas to secure the cut quality and reliability. The cutting was performed with the circularly polarized Gaussian mode.

Figure 1 The CO_2 laser cutting machine used for experimentation

In the experiment two control parameters, i.e., cutting speed (v) and gas pressure (p), were considered, while the laser power was kept constant at 3200 W. By varying the cutting speed at three levels (2, 3 and 6 m/min) it was possible to define three evenly spaced levels of the severance energy E_s (48, 32 and 16 J/mm^2). Severance energy can be defined as the ratio of the laser power to the product of the cutting speed and the sheet thickness.

Nitrogen pressure was also varied at three levels, thus the defined experimental design actually represents full factorial design 3^2, as shown in Tab. 1. This experimental design allows the modeling of quadratic relationships between inputs and considered process responses. To eliminate effects of any noise factors and minimize the systematic error, due to initial differences of laser cutting conditions in experimental trials, the randomization principle was applied [49]. Also, the experimental design was replicated to assess the process variability regarding the resulting kerf width. The initially used manufacturing settings, i.e., default currently used cutting conditions, are: cutting speed $v = 3$ m/min ($E_s = 32$ J/mm^2) and gas pressure $p = 12$ bar, corresponding to experimental trial No. 9. The laser cutting parameters are chosen to cover a wide range of severance energy levels while considering currently used processing conditions in production, general laser cutting recommendations and constraints regarding the realization of a complete cut in each experimental trial. All cut samples were cut at the same laser cutting machine according to previously defined laser cutting conditions and used experimental matrix [50].

Table 1 Tested laser cutting conditions in the experiment

Trial	1	2	3	4	5	6	7	8	9
E_s / J/mm^2	16	48	16	48	16	48	32	32	32
p / bar	10	10	14	14	12	12	10	14	12

For each laser cut specimen multiple measurements of kerf width along straight and curved cut profiles were made. The curved cut profile was cut at cut radius (R20). Measurement locations at three different positions along the straight cut and three different positions along the cut radius are shown in Fig. 2. As shown, kerf width along the straight cut was measured at distances of 15, 20 and 25 mm from the piercing point. Likewise, kerf width along the cut radius was measured at the three equally spaced points along the curved path (at central angles of 15°, 30° and 45°). Measurement of kerf widths was performed with the optical coordinate measuring system (CMS) DeMeet 443 with the resolution of 0.1 µm. This CMS combines telecentric optics and a Sony CCD colour camera for clear and high-quality images. The measuring principle is based on image digitization into an array containing information of the light intensity of each pixel [51]. The speed of data acquisition, high accuracy, precision, and ability to measure inaccessible places and small features represent the main advantages of the used CMS [52].

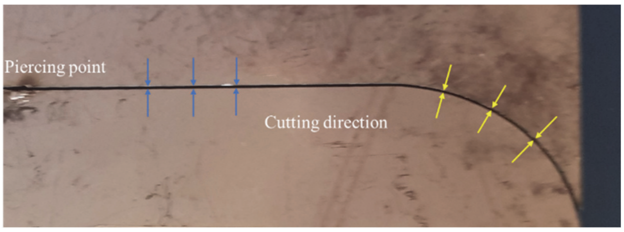


Figure 2 Kerf width measurement locations on the photograph of laser cut specimen

3 RESULTS AND DISCUSSION

The change in average kerf width values with respect to laser cutting conditions is given in Fig. 3. As expected, changes in considered parameters, especially severance energy, i.e., cutting speed, affect the resulting kerf width values. One can observe that for laser cutting regimes with high severance energy, i.e., using lower cutting speeds ($v = 2$ m/min, laser cutting trials 2, 4 and 6), kerf width becomes larger. The possible reason is that with an increase in the cutting speed, the laser beam and material interaction time is decreased as well as severance energy leading to a less melt volume. On the other hand, the effect of nitrogen pressure is less pronounced given that it does not contribute to material melting but only to melt removal from the kerf, in contrast to laser oxygen cutting. These relationships are valid for both cut profiles given the very similar kerf profile patterns obtained in the conducted experiment (Fig. 3). Moreover, it is interesting to notice that when cutting using higher severance energy levels, irrespective of the nitrogen pressure, wider kerf widths are obtained in curved cut profile. Only when using the lowest severance energy, irrespective of the gas pressure, kerf width in the straight profile is somewhat wider than in curved cut profile.

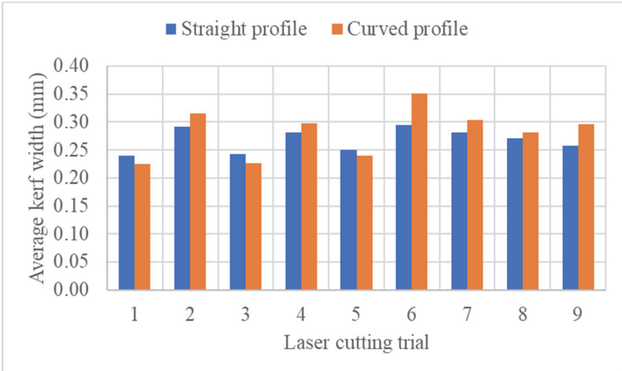


Figure 3 Average kerf width values obtained in experimental trials

Fig. 4 shows the effect of cutting regimes on the kerf width variation, i.e., standard deviation of kerf widths. As could be observed, there are significant variations in different laser cutting conditions, whereby the greatest variation corresponds to the combination of the highest severance energy and the highest nitrogen pressure.

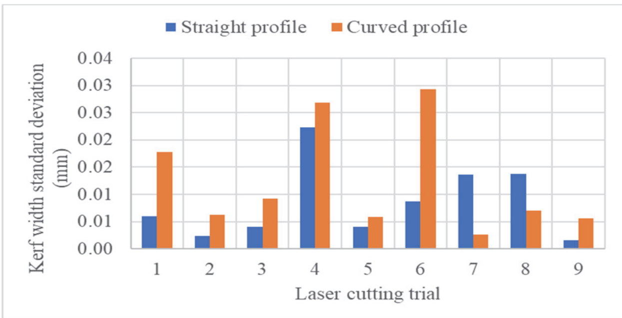


Figure 4 Kerf width variation obtained in experimental trials

This observation coincides with the results of Balarin de Andrade et al. [30], who noted a significant variation of the kerf width values for lower cutting speeds. As explained by Yilbas [53], higher heat concentration is achieved at lower cutting speeds. This may lead to high temperatures that create thermal stresses damaging the workpiece surface, which may ultimately result in greater kerf variations along the cut. The conditions, in which the tendency to reduce the kerf width variation is evident, can be realized by different severance energy levels, but still with lower to medium pressure levels (up to 12 bar). Chen et al. [54] observed that for particular stand-off distances the use of high assisting gas pressures may induce fluctuations of shear forces and pressure gradient, which ultimately hinder melt removal and negatively affect the cut quality. Bearing in mind the previous considerations, one can argue that the observations made are in accordance with the findings from the previous research.

For the entire experiment, the mean effect of cutting profile on kerf width and its variation is illustrated in Fig. 5. It can be argued that regardless of the selected cutting parameters, kerf width is slightly narrower in the straight cut profile in comparison to the curved cut profile and one can expect better repeatability and uniformity due to a smaller variation. These indications agree well with the results of Sharma et al. [37], who noted that kerf unevenness is more likely to occur along the curved cut profile. When producing a full circle or a part of one (arc, radius), the CNC control must continuously change the ratios between the drive motors for each increment of arc, which represents an additional challenge for the computer beyond linear interpolation [55]. Therefore, drive motors synchronization and simultaneous coordinated movements in the XY plane while guiding the cutting head along a curve cut profile may additionally affect the accuracy of the laser cutting process.

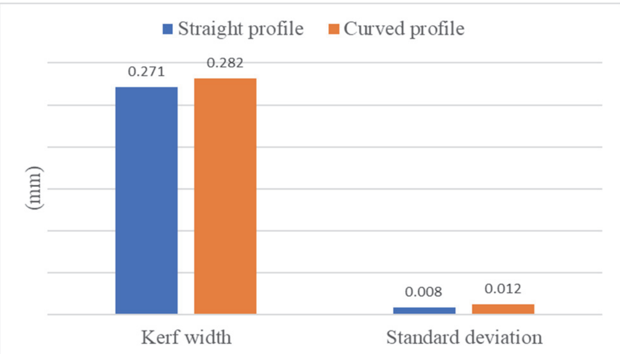


Figure 5 The effect of cut profile on kerf width and its variation in the experiment

Using the experimental kerf data one can develop models for the prediction of kerf width and its variation (in terms of standard deviation σ) for both cut profiles and an arbitrarily chosen combination of severance energy and nitrogen pressure. By using the least square method one can develop the following quadratic empirical models:

$$K_{wstraight} = 0.577 + 0.0276 \cdot E_s - 0.062 \cdot p + \\ +5.47 \cdot 10^{-5} \cdot E_s \cdot p - 3.13 \cdot 10^{-5} \cdot E_s^2 + 0.003 \cdot p^2, \\ R = 0.946 \tag{1}$$

$$K_{wcurved} = -0.0007 + 0.0048 \cdot E_s + 0.031 \cdot p + \\ +8.59 \cdot 10^{-5} \cdot E_s \cdot p - 5.08 \cdot 10^{-5} \cdot E_s^2 - 0.002 \cdot p^2, \\ R = 0.986 \tag{2}$$

$$\sigma_{straight} = 0.239 - 0.0014 \cdot E_s - 0.037 \cdot p + \\ +1.71 \cdot 10^{-4} \cdot E_s \cdot p - 7.03 \cdot 10^{-6} \cdot E_s^2 + 0.001 \cdot p^2, \\ R = 0.899 \tag{3}$$

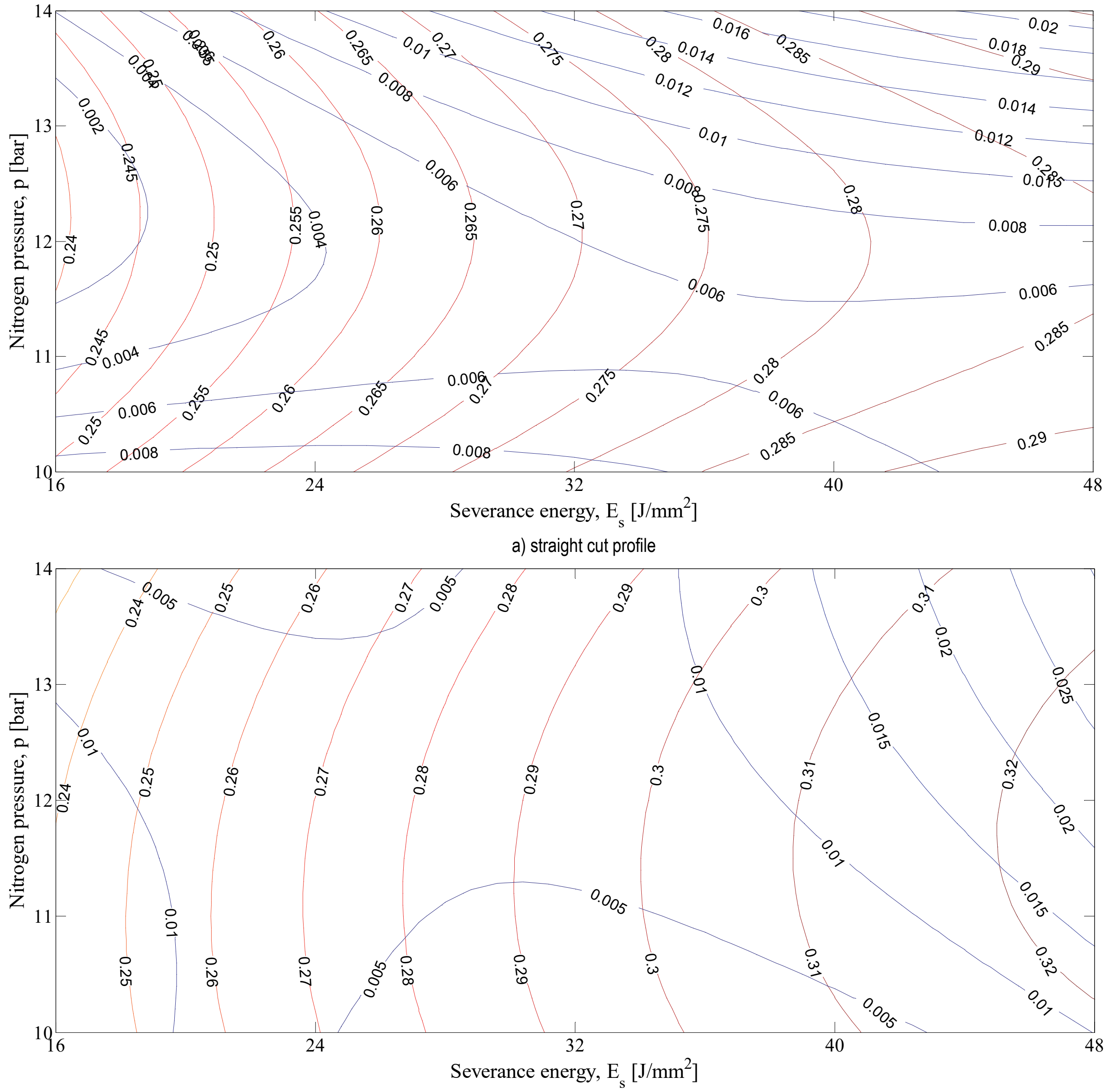
$$\sigma_{curved} = 0.041 - 0.0052 \cdot E_s + 0.0058 \cdot p + \\ +2.29 \cdot 10^{-4} \cdot E_s \cdot p + 4.24 \cdot 10^{-5} \cdot E_s^2 - 0.0005 \cdot p^2, \\ R = 0.906 \tag{4}$$

Differences between the predicted and actual values for straight and curved cut profiles are quite acceptable given the high values of correlation coefficients. Analysis of the possible interaction effect of the severance energy and nitrogen pressure on kerf width and its variation for both cut profiles is based on overlay contour plots given in Fig. 6. For both straight and curved cut profiles, the dominant effect of the severance energy on the kerf width values is evident, whereas the effect of the nitrogen pressure is almost negligible, which confirms the previously made discussion. The resulting overlay contour plots reveal that there are no significant interaction effects of the considered input parameters as well as that changes in kerf width in straight and curved profiles have similar patterns. However, the contour plot shape for the curved cut profile is more of a concave type, indicating, for the same combination of severance energy and nitrogen pressure, a tendency of obtaining higher kerf width values.

From the aspect of kerf width variation, it is evident from Fig. 6 that contour curves are nonlinear, indicating a pronounced interaction effect of the severance energy and nitrogen pressure on the resulting kerf width variation, both for straight and curved cut profiles. From the overlay contour plots one can also observe that, although the regions for simultaneous minimization of kerf width and its variation on straight and curved profiles may not necessarily coincide, combinations of higher severance energy and nitrogen pressure levels are not favourable for the minimization of kerf width and its variation. As concluded by Sharma et al. [37], the optimal combination of cutting parameter values may be entirely different when comparing cut profiles (straight and curved). The obtained results and analysis of contour plots also agree well with the findings of Parthiban et al. [17], who, based on the ANOVA results for kerf width for straight and curved profile, observed pronounced effects of cutting speed and laser power, i.e., severance energy, without significant two-factorial interactions of cutting speed, laser power and nitrogen pressure.

Based on Fig. 6, one can expect that a further decrease in severance energy will result in a kerf width decrease. However, it is necessary to keep in mind the minimum required severance energy levels necessary to establish a continuous cutting front and avoid process disruption [34]. Also, particularly in laser fusion cutting, too large kerf width reduction prevents the efficient melt removal from the kerf and ultimately can promote dross formation. It should be noted that within the two-dimensional experimental space dross formation was not evident, probably due to appropriate focusing and a well-chosen process window of severance energy and nitrogen pressure.

As previously mentioned, the default manufacturing setting (v = 3 m/min, E_s = 32 J/mm^2, p = 12 bar, experimental trial No. 9) yielded the average kerf width of K_w = 0.275 mm and the average kerf width variation of σ = 0.0035 mm, on both the straight and curved cut profile. At the same time, as previously observed from the experimental results, a particular example, i.e., experimental trial No. 5 (v = 6 m/min, E_s = 16 J/mm^2, p = 12 bar) yielded the average kerf width of K_w = 0.241 mm and the average kerf width variation of σ = 0.0049 mm, on both the straight and curved profile. It should also be emphasized that these two conditions significantly differ in terms of productivity rates given that twice the cutting speed is used in experimental trial No. 5.



a) straight cut profile

b) curved cut profile

Figure 6 Overlay contour plots showing changes in kerf width Kw (▬) and its variation σ (▬)

Given that the cutting speed is in an indirect relationship with the width of the heat affected zone (HAZ) [12, 56], a zone of the base material with altered microstructure and mechanical properties due to generated heat [56], one can argue that it is also beneficial for securing high quality cutting of heat-sensitive sections [57] and avoiding undesirable effects of altered internal microstructure and properties within HAZ. This previous observation, but also others from the experiment, point to the fact that compromise solutions are needed regarding kerf width and its variation, but also other important laser cutting performances. To this aim, based on the developed empirical prediction models, prescribed allowable target values, and bounds on the mean kerf width and its standard deviation, one can formulate and solve multi-response optimization problems so as to identify more favourable cutting conditions.

It is clear that the kerf width is technological parameter dependent on multiple process parameters, such as laser power, cutting speed, focus position, etc. and as such during the actual cutting operation cannot be altered. However, for the adopted laser cutting regime, and kerf width estimates for straight and curved cut profiles based on developed models, one can more accurately determine the tool radius which is used for altering the kerf position relative to the programmed cutting contour. Since this study analysed two kerf profiles, the tool radius can be estimated as the half average of the kerf widths along the straight and curved cut profiles. In this way one may ensure improved contour accuracy and tighter dimensional tolerances.

4 CONCLUSION

The present paper focused on the analysis of kerf width and its variation in CO_2 laser cutting of straight and curved cut profiles under different processing conditions. The main contribution is the analysis and modeling of the effects of severance energy and nitrogen pressure on the considered outputs, with the possibility to identify process windows for achieving a highly repeatable laser cutting process while meeting prespecified kerf width values. The following conclusions, based on the conducted analysis and experimental/modeling results, can be drawn:

- The change in laser cutting conditions, in terms of severance energy and nitrogen pressure, cause a similar qualitative and quantitative change in the kerf width for both cut profiles (straight and curved), wherein kerf width in the curved cut profile is somewhat wider (on average 5% for the entire experiment). At the same time, the influence of severance energy is dominant, while the effect of nitrogen pressure is almost negligible.
- Regarding the kerf width variation, it tends to be more pronounced for the curved cut profile, while for both cut profiles the combination of the highest severance energy and the highest nitrogen pressure results in the highest dispersion of kerf width data. In sum, for the given set of laser cutting parameters one can expect narrower kerf widths and better process repeatability when cutting straight profiles in comparison to curved profiles.
- Analysis of the developed empirical models further reveals the existence of the interaction effect of the severance energy and nitrogen pressure on the resulting kerf width variation, making the nonlinearity regarding kerf width variation more pronounced than in the case of kerf width, for both cut profiles.
- Experimental and empirical modeling results indicate that laser cutting conditions which would be the most favourable for the minimization of four considered outputs (kerf width and its variation along straight and curved cut profiles) do not necessarily coincide. This clearly indicates a need for multi-response optimization, not necessarily focused only on kerf geometry but also on other important performances, particularly in the case of laser series cutting of different features with multiple geometrical characteristics of various dimensions.

In addition to the analysis focused only on kerf width and its variation of straight and curved profiles, the limitation of this study is related to the consideration of a single curve profile, single sheet material type and thickness and low experimental dimensionality. The consideration of these issues will guide future research. Still, the conducted research and applied methodology represents a basic step in an effort to obtain more uniform kerf width of specified size along with minimal variations, which is very significant from the industrial practice point of view.

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5 REFERENCES

[1] Pocorni, J., Petring, D., Powell, J., Deichsel, E., & Kaplan, A. F. (2016). The effect of laser type and power on the efficiency of industrial cutting of mild and stainless steels. *Journal of Manufacturing Science and Engineering, 138*(3), 031012. https://doi.org/10.1027/0269-8803.20.4.253

[2] Vagheesan, S. & Govindarajulu, J. (2021). Comparative regression and neural network modeling of roughness and kerf width in CO_2 laser cutting of aluminium. *Technical Gazette, 28*(5), 1437-1441. https://doi.org/10.17559/TV-20190130153849

[3] Girdu, C. C., Gheorghe, C., Radulescu, C., & Cirtina, D. (2021). Influence of process parameters on cutting width in CO_2 laser processing of hardox 400 steel. *Applied Sciences, 11*(13), 5998. https://doi.org/10.3390/app11135998

[4] Alsaadawy, M., Dewidar, M., Said, A., Maher, I., & Shehabeldeen, T. A. (2024). A comprehensive review of studying the influence of laser cutting parameters on surface and kerf quality of metals. *The International Journal of Advanced Manufacturing Technology, 130*(3), 1039-1074. https://doi.org/10.1007/s00170-023-12768-1

[5] Wandera, C. (2010). *Performance of high power fibre laser cutting of thick-section steel and medium-section aluminium*, PhD Thesis, Lappeenranta University of Technology, Finland.

[6] Powell, J. (1993). *CO_2 Laser Cutting*. Berlin: Springer-Verlag. https://doi.org/10.1007/978-1-4471-3384-1

[7] Gopal, P. M., Kavimani, V., Gupta, K., & Marinkovic, D. (2023). Laser-based manufacturing of ceramics: a review. *Micromachines, 14*(8), 1564. https://doi.org/10.3390/mi14081564

[8] Caristan, C. L. (2004). *Laser Cutting Guide for Manufacturing*. Society of manufacturing engineers.

[9] Ghany, K. A. & Newishy, M. (2005). Cutting of 1.2 mm thick austenitic stainless steel sheet using pulsed and CW Nd: YAG laser. *Journal of Materials Processing Technology, 168*(3), 438-447. https://doi.org/10.1016/j.jmatprotec.2005.02.251

[10] Aloke, R., Girish, V., Scrutton, R. F., & Molian, P. A. (1997). A model for prediction of dimensional tolerances of laser cut holes in mild steel thin plates. *International Journal of Machine Tools and Manufacture, 37*(8), 1069-1078. https://doi.org/10.1016/S0890-6955(96)00090-9

[11] Madić, M., Mladenović, S., Gostimirović, M., Radovanović, M., & Janković, P. (2020). Laser cutting optimization model with constraints: Maximization of material removal rate in CO_2 laser cutting of mild steel. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 234*(10), 1323-1332. https://doi.org/10.1177/0954405420911529

[12] Yilbas, B. S. (2008). Laser cutting of thick sheet metals: Effects of cutting parameters on kerf size variations. *Journal of Materials Processing Technology, 201*(1-3), 285-290. https://doi.org/10.1016/j.jmatprotec.2007.11.265

[13] Uslan, I. (2005). CO_2 laser cutting: kerf width variation during cutting. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 219*(8), 571-577. https://doi.org/10.1243/095440505X32508

[14] Genna, S., Menna, E., Rubino, G., & Tagliaferri, V. (2020). Experimental investigation of industrial laser cutting: The effect of the material selection and the process parameters on the kerf quality. *Applied Sciences, 10*(14), 4956. https://doi.org/10.3390/app10144956

[15] Madić, M., Jovanović, D., & Janković, P. (2024). Fiber laser cutting technology: Pilot case study in mild steel cutting. *Spectrum of Mechanical Engineering and Operational Research, 1*(1), 1-9. https://doi.org/10.31181/smeor1120241

[16] Keles, O. & Oner, U. (2012). Laser cutting process: Influence of workpiece thickness and laser pulse frequency

on the cut quality. *Arabian Journal for Science and Engineering, 37*(8), 2277-2286. https://doi.org/10.1007/s13369-012-0306-2

[17] Parthiban, A., Sathish, S., Chandrasekaran, M., & Ravikumar, R. (2017). Optimization of CO_2 Laser Cutting Parameters on Austenitic Type Stainless Steel Sheet. *IOP Conference Series: Materials Science and Engineering, 183*(1), 012022. https://doi.org/10.1088/1757-899X/183/1/012022

[18] Eltawahni, H. A., Hagino, M., Benyounis, K. Y., Inoue, T., & Olabi, A. G. (2012). Effect of CO_2 laser cutting process parameters on edge quality and operating cost of AISI316L. *Optics & Laser Technology, 44*(4), 1068-1082. https://doi.org/10.1016/j.optlastec.2011.10.008

[19] Parthiban, A., Sathish, S., Ravikumar, R., & Prakash, P. (2020). Experimental investigation and fuzzy logic modelling of CO_2 laser cutting parameter for AA6061-T6 sheet. *International Journal of Rapid Manufacturing, 9*(1), 48-57. https://doi.org/10.1504/IJRAPIDM.2020.104424

[20] Choudhury, I. A. & Chuan, P. C. (2013). Experimental evaluation of laser cut quality of glass fibre reinforced plastic composite. *Optics and Lasers in Engineering, 51*(10), 1125-1132. https://doi.org/10.1016/j.optlaseng.2013.04.017

[21] Riveiro, A., Quintero, F., Lusquiños, F., Del Val, J., Comesaña, R., Boutinguiza, M., & Pou, J. (2017). Laser cutting of carbon fiber composite materials. *Procedia Manufacturing, 13*, 388-395. https://doi.org/10.1016/j.promfg.2017.09.026

[22] Singh, T., Verma, V., & Pandey, A. K. (2023). Prediction of optimum parameters in the laser cutting of titanium alloy sheet. *NanoWorld Journal, 9*(S1), S182-S187. https://doi.org/10.17756/nwj.2023-s1-037

[23] Yilbas, B. S., Shaukat, M. M., & Ashraf, F. (2017). Laser cutting of various materials: Kerf width size analysis and life cycle assessment of cutting process. *Optics & Laser Technology, 93*, 67-73. https://doi.org/10.1016/j.optlastec.2017.02.014

[24] Bartl, N. & Bergmann, H. W. (1997). Influence of Processing Speed on Cut Quality in Laser Beam Gas Cutting of Copper. *Proceedings of the Lasers in Materials Processing, 3097*, 70-78. https://doi.org/10.1117/12.281134

[25] Caiazzo, F., Curcio, F., Daurelio, G., & Minutolo, F. M. C. (2005). Laser cutting of different polymeric plastics (PE, PP and PC) by a CO_2 laser beam. *Journal of Materials Processing Technology, 159*(3), 279-285. https://doi.org/10.1016/j.jmatprotec.2004.02.019

[26] Haddadi, E., Moradi, M., Ghavidel, A. K., Ghavidel, A. K., & Meiabadi, S. (2019). Experimental and parametric evaluation of cut quality characteristics in CO_2 laser cutting of polystyrene. *Optik, 184*, 103-114. https://doi.org/10.1016/j.ijleo.2019.03.040

[27] Guo, X., Deng, M., Hu, Y., Wang, Y., & Ye, T. (2021). Morphology, mechanism and kerf variation during CO_2 laser cutting pine wood. *Journal of Manufacturing Processes, 68* (Part A), 13-22. https://doi.org/10.1016/j.jmapro.2021.05.036

[28] Kubovský, I., Krišťák, Ľ., Suja, J., Gajtanska, M., Igaz, R., Ružiak, I., & Réh, R. (2020). Optimization of parameters for the cutting of wood-based materials by a CO_2 laser. *Applied Sciences, 10*(22), 8113. https://doi.org/10.3390/app10228113

[29] Riveiro, A., Mejías, A., Soto, R., Quintero, F., Del Val, J., Boutinguiza, M., Lusquiños, F., Pardo, J., & Pou, J. (2016). CO_2 laser cutting of natural granite. *Optics & Laser Technology, 76*, 19-28. https://doi.org/10.1016/j.optlastec.2015.07.018

[30] Andrade, A. C. B. D., Aguiar, P. R., Viera, M. A. A., Alexandre, F. A., Junior, P. O., & Dotto, F. R. (2019). Monitoring of the Ceramic Kerf During the Laser Cutting Process through Piezoelectric Transducer. *6th International Electronic Conference on Sensors and Applications*, *Proceedings, 42*(1), 44. https://doi.org/10.3390/ecsa-6-06529

[31] Vasileska, E., Pacher, M., & Previtali, B. (2022). In-line monitoring of focus shift by kerf width detection with coaxial thermal imaging during laser cutting. *The International Journal of Advanced Manufacturing Technology, 118*(7), 2587-2600. https://doi.org/10.1007/s00170-021-07893-8

[32] Sichani, E. F., De Keuster, J., Kruth, J. P., & Duflou, J. R. (2010). Monitoring and adaptive control of CO_2 laser flame cutting. *Physics Procedia, 5*, 483-492. https://doi.org/10.1016/j.phpro.2010.08.076

[33] BS EN ISO 9013:2020 Thermal cutting. Classification of thermal cuts. Geometrical product specification and quality tolerances.

[34] Steen, W. M. & Mazumder, J. (2010). *Laser Material Processing*. Springer science & business media. https://doi.org/10.1007/978-1-84996-062-5

[35] Madić, M., Gostimirović, M., Rodić, D., Radovanović, M., & Coteaţă, M. (2022). Mathematical modelling of the CO_2 laser cutting process using genetic programming. *Facta Universitatis, Series: Mechanical Engineering, 20*(3), 665-676. https://doi.org/10.22190/FUME210810003M

[36] Di Pietro, P. & Yao, Y. L. (1994). An investigation into characterizing and optimizing laser cutting quality - a review. *International Journal of Machine Tools and Manufacture, 34*(2), 225-243. https://doi.org/10.1016/0890-6955(94)90103-1

[37] Sharma, A., Yadava, V., & Rao, R. (2010). Optimization of kerf quality characteristics during Nd: YAG laser cutting of nickel based superalloy sheet for straight and curved cut profiles. *Optics and Lasers in Engineering, 48*(9), 915-925. https://doi.org/10.1016/j.optlaseng.2010.03.005

[38] Pandey, A. K. & Dubey, A. K. (2013). Fuzzy expert system for prediction of kerf qualities in pulsed laser cutting of titanium alloy sheet. *Machining Science and Technology, 17*(4), 545-574. https://doi.org/10.1080/10910344.2013.806182

[39] Chaki, S., Ghosal, S., & Bathe, R. N. (2012). Optimisation of kerf quality during pulsed Nd: YAG laser cutting of aluminium alloy sheet. *Proceedings of the International Congress "Machines, Technologies, Materials", 1*, 61-64.

[40] Das, P. P., Kumar, S., Singh, Y., Das, S., & Sinha, A. K. (2018). Multi-objective optimization of Nd: YAG laser cutting of nickel-based superalloy sheet using grey-fuzzy approach. *IOP Conference Series: Materials Science and Engineering, 377*(1), 12196. https://doi.org/10.1088/1757-899X/377/1/012196

[41] Gautam, G. D. & Pandey, A. K. (2018). Teaching learning algorithm based optimization of kerf deviations in pulsed Nd: YAG laser cutting of Kevlar-29 composite laminates. *Infrared Physics & Technology, 89*, 203-217. https://doi.org/10.1016/j.infrared.2017.12.017

[42] Rajamani, D. & Tamilarasan, A. (2016). Fuzzy and regression modeling for Nd: YAG laser cutting of Ti-6Al-4V superalloy sheet. *Journal for Manufacturing Science and Production, 16*(3), 153-162. https://doi.org/10.1515/jmsp-2016-0010

[43] Khoshaim, A. B., Elsheikh, A. H., Moustafa, E. B., Basha, M., & Showaib, E. A. (2021). Experimental investigation on laser cutting of PMMA sheets: Effects of process factors on kerf characteristics. *Journal of Materials Research and Technology, 11*, 235-246. https://doi.org/10.1016/j.jmrt.2021.01.012

[44] Mishra, D. R., Dutt, G. G., Prakash, D., Bajaj, A., Sharma, A., Bisht, R., & Gupta, S. (2020). Optimization of kerf deviations in pulsed Nd: YAG laser cutting of hybrid composite laminate using GRA. *FME Transactions, 48*(1), 109-116. https://doi.org/10.5937/fmet2001109M

[45] Najjar, I. M. R., Sadoun, A. M., Abd Elaziz, M., Abdallah, A. W., Fathy, A., & Elsheikh, A. H. (2022). Predicting kerf quality characteristics in laser cutting of basalt fibers reinforced polymer composites using neural network and

chimp optimization. *Alexandria Engineering Journal, 61*(12), 11005-11018. https://doi.org/10.1016/j.aej.2022.04.032

[46] Rao, R. & Yadava, V. (2009). Multi-objective optimization of Nd: YAG laser cutting of thin superalloy sheet using grey relational analysis with entropy measurement. *Optics & Laser Technology, 41*(8), 922-930. https://doi.org/10.1016/j.optlastec.2009.03.008

[47] Joshi, P. & Sharma, A. (2018). Optimization of process parameters during laser beam cutting of Ni-based superalloy thin sheet along curved profile using grey-fuzzy methodology. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 40*(8), 389. https://doi.org/10.1007/s40430-018-1302-6

[48] Bhattacharya, S. & Chakraborty, S. (2023). Prediction of responses in a CNC milling operation using random forest regressor. *Facta Universitatis, Series: Mechanical Engineering, 21*(4), 685-700. https://doi.org/10.22190/FUME210728071B

[49] Montgomery, D. C. (2017). *Design and Analysis of Experiments*. John Wiley & Sons.

[50] Madić, M., Petrović, G., Petković, D., & Janković, P. (2024). Traditional and integrated MCDM approaches for assessment and ranking of laser cutting conditions. *Spectrum of Mechanical Engineering and Operational Research, 1*(1), 250-257. https://doi.org/10.31181/smeor1120241

[51] Pilný, L., De Chiffre, L., Píška, M., & Villumsen, M. F. (2012). Hole quality and burr reduction in drilling aluminium sheets. *CIRP Journal of Manufacturing Science and Technology, 5*(2), 102-107. https://doi.org/10.1016/j.cirpj.2012.03.005

[52] Jotić, G., Štrbac, B., Toth, T., Blanuša, V., Dovica, M., & Hadžistević, M. (2023). The analysis of metrological characteristics of different coordinate measuring systems. *Technical Gazette, 30*(1), 32-38. https://doi.org/10.17559/TV-20220204091212

[53] Yilbas, B. S. (2017). *The Laser Cutting Process: Analysis and Applications*. Elsevier.

[54] Chen, K., Yao, Y. L., & Modi, V. (2001). Gas dynamic effects on laser cut quality. *Journal of Manufacturing Processes, 3*(1), 38-49. https://doi.org/10.1016/S1526-6125(01)70032-1

[55] Fitzpatrick, M. (2014). *Machining and CNC Technology*. New York: McGraw-Hill.

[56] Miraoui, I., Boujelbene, M., & Zaied, M. (2016). High-power laser cutting of steel plates: heat affected zone analysis. *Advances in Materials Science and Engineering, 2016*(1), 1242565. https://doi.org/10.1155/2016/1242565

[57] Mushtaq, R. T., Wang, Y., Rehman, M., Khan, A. M., & Mia, M. (2020). State-of-the-art and trends in CO_2 laser cutting of polymeric materials - a review. *Materials, 13*(17), 3839. https://doi.org/10.3390/ma13173839

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